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13. ABSTRACT (Maximum 200 words)

In modern spy movies such as *Enemy of the State* and *Patriot Games*, scientists magnify digital satellite imagery to determine the identities of people captured on surveillance video. These individuals appear rather blocky at the coarsest resolution scales because of undersampling by the image sensor array, but they become remarkably clear after zooming in on a particular region-of-interest. Although real-world video enhancement algorithms are not capable of calculating the perfect results produced in Hollywood, additional details can be extracted from an image sequence by integrating several neighboring frames that contain subpixel-resolution scene/object motion. The five most important research results obtained through this grant activity related to the Bayesian estimation of high-resolution imagery from low-resolution digital video include: (1) nonlinear filtering of subpixel motion vectors for improved super-resolution video enhancement; (2) estimation of subpixel motion fields from segmented image sequences; (3) super-resolution enhancement of compressed digital video; (4) multiframe integration via the projective transformation with automated block matching feature point pair selection; and (5) development of a Windows-based video enhancement software tool. As a follow-up to these R&D activities, the PI has been attempting to secure funding to market super-resolution enhancement technologies to law enforcement and national security agencies.

14. SUBJECT TERMS
Digital Video, Enhancement, High-Resolution, Image Compression, Image Processing, Image Resolution, Image Interpolation, MPEG, Multiframe Integration, Multisensor, Reconnaissance, Sensor Fusion, Surveillance, Super-Resolution, Upsampling, Video Processing

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BAYESIAN ESTIMATION OF HIGH-RESOLUTION IMAGERY FROM LOW-RESOLUTION VIDEO SEQUENCES AND MULTISENSOR DATA SETS

FINAL PROGRESS REPORT

DR. RICHARD R. SCHULTZ

08 JAN 2002

U.S. ARMY RESEARCH OFFICE

GRANT NUMBER DAAH04-96-1-0449

UNIVERSITY OF NORTH DAKOTA

1. Foreword

Intentionally omitted (optional).

2. Table of Contents

3. List of Appendixes, Illustrations and Tables

None.

4. Statement of the Problem Studied

4.1. Abstract from Standard Form 298

In modern spy movies such as *Enemy of the State* and *Patriot Games*, scientists magnify digital satellite imagery to determine the identities of people captured on surveillance video. These individuals appear rather blocky at the coarsest resolution scales because of undersampling by the image sensor array, but they become remarkably clear after zooming in on a particular region-of-interest. Although real-world video enhancement algorithms are not capable of calculating the perfect results produced in Hollywood, additional details can be extracted from an image sequence by integrating several neighboring frames that contain subpixel-resolution scene/object motion. The five most important research results obtained through this grant activity related to the Bayesian estimation of high-resolution imagery from low-resolution digital video include: (1) nonlinear filtering of subpixel motion vectors for improved super-resolution video enhancement; (2) estimation of subpixel motion fields from segmented image sequences; (3) super-resolution enhancement of compressed digital video; (4) multiframe integration via the projective transformation with automated block matching feature point pair selection; and (5) development of a Windows-based video enhancement software tool. As a follow-up to these R&D activities, the PI has been attempting to secure funding to market super-resolution enhancement technologies to law enforcement and national security agencies.

4.2. Comprehensive problem description

In modern spy movies such as *Patriot Games* and *Enemy of the State*, whenever an analyst magnifies a satellite image on a computer, it appears as a perfect, highly detailed picture. In reality, enlarging a digital image by using the magnifying glass tool in Adobe® Photoshop® generally results in a very blocky scene. Real-world video enhancement algorithms are simply not capable of calculating the perfect results produced in Hollywood; however, additional visual information can be extracted from a digital image sequence by temporally integrating several neighboring frames to compute a super-resolution video still. Provided that people and objects move between the digital video frames, this motion can be exploited to improve definition and to actually see details where there were once blocky pixels.

The concepts of sampling and image resolution are extremely important, in the context of capturing a single digital picture using a flatbed scanner or a digital still image camera, as well as capturing a sequence of pictures using a digital video (DV) camera. The resulting digital imagery may be *undersampled*, in which each pixel appears blocky when viewed close-up. A $20 bill scanned at various resolutions (dots per inch, or dpi) can provide an intuitive understanding of this concept. As another example from the remote sensing scientific community, the Landsat 7 satellite provides 30-meter resolution imagery to its end users. In essence, this means that each image pixel represents a 30-meter by 30-meter square region on the Earth's surface. Obviously, there are a large number of details contained within a single Landsat 7 pixel that cannot be observed from the data directly. Postprocessing the data using various interpolation methods can help to extract some additional details from the digital imagery.

The human visual system appears to be capable of temporally integrating information in a video sequence in such a way that the perceived spatial resolution of the sequence appears much higher than the actual spatial resolution of an individual frame. This effect is not too surprising, given that neighboring frames within an image sequence contain slightly different, but unique, information. To compute a super-resolution video still from the original low-resolution data, the research conducted for this project relies on a method known as Bayesian maximum *a posteriori* (MAP) estimation. Bayesian estimation is a stochastic regularization technique used to reformulate ill-posed inverse problems such as image restoration, reconstruction, and enhancement as well-posed problems with unique solutions. An edge-preserving Markov random field prior density is assumed for spatial images that accurately models piece-wise smooth data, and a Gaussian density is assumed for the modeling error and noise. The Bayesian estimation technique results in a highly-computational, iterative optimization problem that can be solved numerically using custom software. A wide variety of simulations have shown that this nonlinear resolution

enhancement technique results in image estimates which are visually and quantitatively superior to linear estimates generated by least squares methods.

Developing an accurate video observation model for the image sequence data is perhaps the most important component of any super-resolution video enhancement algorithm. In modeling digital video sequences, the motion between frames must be estimated so that temporal correlations along object trajectories can be incorporated in the model. A number of projects supported by this grant are concerned with the accurate estimation of subpixel motion vectors for super-resolution video enhancement. Furthermore, compressed data is becoming the standard in video communications; thus, several projects involve the super-resolution enhancement of compressed video, specifically the MPEG-1 and MPEG-2 formats. Unfortunately, image and video enhancement are extremely costly from a computational perspective, such that a great deal of processing time is required to generate an image estimate. For this reason, a "quick-and-dirty" method of multiframe integration is proposed, using the projective camera model for global scene transformations. An interesting byproduct of this work surrounds the automated registration of similar and dissimilar sensor channels using block matching feature point pair selection. Finally, to take super-resolution enhancement technology from the research laboratory to the desktops of law enforcement agencies, a user-friendly system must be developed. An effort to develop a Windows-based software tool for the super-resolution enhancement of surveillance video sequences is described in this report.

These research results are particularly useful for cleaning up surveillance and reconnaissance image sequences. For instance, after a crime takes place, it is often difficult to obtain an adequate picture of the suspects from the surveillance video. With super-resolution video enhancement, multiple video frames can be combined to extract a high-resolution image of the suspects and their distinguishing features, which in turn helps law enforcement agents identify the perpetrators. Quite obviously, there are a number of national security-related applications on the horizon.

Dr. Harry Nyquist, one of the pioneers of modern-day telecommunications technology and a graduate of the University of North Dakota (BSEE 1914; MSEE 1915), originally developed the sampling theorem, one of the most significant discoveries in telecommunications and signal processing. This theorem dictates the minimum sampling frequency necessary for the perfect reconstruction of a continuous-time signal from its discrete-time samples. Because of the massive increase in desktop computing power during this past decade, we are just now beginning to utilize and advance Dr. Nyquist's theories in the digital image and video processing product development arena.

5. Summary of the Most Important Results

The five most important research and development projects related to the Bayesian estimation of high-resolution imagery from low-resolution image sequences conducted throughout the duration of this grant include:

1. Nonlinear filtering of subpixel motion vectors for improved super-resolution video frame enhancement;
2. Estimation of subpixel-resolution motion fields from segmented image sequences;
3. Super-resolution enhancement of compressed digital video;
4. Multiframe integration via the projective transformation with automated block matching feature point pair selection; and
5. Development of a Windows-based software tool for the super-resolution enhancement of surveillance image sequences.

In addition, two other projects will be described, since this ARO support was extremely vital in initiating the following ongoing research efforts:

1. Super-resolution enhancement of night vision image sequences; and
2. Spacecraft systems engineering – the initiation of a multidisciplinary design project at the University of North Dakota.

Each of these projects will be summarized, with all relevant publications/presentations listed.

5.1. Nonlinear filtering of subpixel motion vectors for improved super-resolution video frame enhancement

Super-resolution enhancement algorithms are used to estimate a high-resolution video still (HRVS) from several low-resolution frames, provided that entire scenes or individual objects within a digital video sequence move in subpixel displacements. This requires the estimation of subpixel-resolution motion vectors with respect to the target picture undergoing resolution enhancement, prior to computational video frame integration. However, estimating accurate subpixel motion vectors between two low-resolution, noisy video frames has proven to be a formidable challenge. Applying block matching or optical flow estimation to upsampled frames from the image sequence generally results in relatively poor subpixel motion vectors, and consequently inaccurate regions within a particular super-resolution enhanced video still. To improve the visual quality of the enhanced frame, the motion vector estimates can be refined through the application of various nonlinear filters, with the most promising results obtained through α-trimmed mean filtering. Nonlinear filtering eliminates most of the outlier motion estimation errors, resulting in a more consistent set of subpixel motion vectors. Consequently, an improvement in visual quality is achievable in the corresponding HRVS estimate. Through simulations, it is shown that nonlinear motion vector filtering is more appropriate than linear finite impulse response filtering for improving the visual quality of the super-resolved frames.

The following conference publication/presentation based on this research was supported in part by this ARO grant:

Richard R. Schultz, "Nonlinear Filtering of Subpixel Motion Vectors for Improved Super-Resolution Video Frame Enhancement." Invited paper in *Proceedings of the 2001 IEEE-EURASIP Workshop on Nonlinear Signal and Image Processing* (on CD-ROM), Special Session on Nonlinear Methods for Signal Resolution Enhancement, Baltimore, MD, 3-6 Jun 2001. Presented at the workshop by Richard R. Schultz.

5.2. Estimation of subpixel-resolution motion fields from segmented image sequences

Super-resolution enhancement algorithms are used to estimate a high-resolution video still (HRVS) from several low-resolution frames, provided that objects within the image sequence move with subpixel increments. However, estimating an accurate subpixel-resolution motion field between two low-resolution, noisy video frames has proven to be a formidable challenge. Upsampling the image sequence frames followed by the application of block matching, optical flow estimation, or Bayesian motion estimation results in relatively poor subpixel-resolution motion fields, and consequently inaccurate regions within the super-resolution enhanced video still. This is particularly true for large interpolation factors (greater than or equal to 4). To improve the quality of the subpixel motion fields and the corresponding HRVS, motion can be estimated for each object within a segmented image sequence. First, a reference video frame is segmented into its constituent objects, and a mask is generated for each object that represents its spatial location. As described previously, subpixel-resolution motion estimation is then conducted by video frame upsampling followed by the application of a motion estimation algorithm. Finally, the motion vectors are averaged over the region of each mask by applying an α-trimmed mean filter to the horizontal and vertical components separately. Since each object moves as a single entity, averaging the displacement vectors in this manner eliminates many of the motion estimation errors and results in much more consistent subpixel motion fields. A substantial improvement is also visible within particular regions of the HRVS estimates. Subpixel-resolution motion fields and HRVS estimates are computed for interpolation factors of 2, 4, 8, and 16, to examine the benefits of object segmentation and motion field averaging.

The following conference publication/presentation based on this research was supported in part by this ARO grant:

Richard R. Schultz and Robert L. Stevenson, "Estimation of Subpixel-Resolution Motion Fields from Segmented Image Sequences." In *Proceedings of SPIE – Sensor Fusion: Architectures, Algorithms, and Applications II (AeroSense '98)*, volume 3376, pages 90-101, Orlando, FL, 13-17 Apr 1998. Presented at the conference by Richard R. Schultz.

5.3. Super-resolution enhancement of compressed digital video

As a preprocessing step to the analysis of individual video frames, super-resolution enhancement can be used to extract additional spatial detail from an image sequence through the temporal integration of multiple frames. Due to the intra-coded macroblocks contained within an MPEG image sequence and the overlap of coded, motion-compensated macroblocks between frames, it is possible to perform super-resolution enhancement on compressed video by temporally integrating a short subsequence of decoded pictures. The intra-coded I-picture is a logical candidate for enhancement, since it contains the most unique information among the I-, P-, and B-picture types. For an MPEG-1 image sequence coded in the B-B-I-B-B-P-B-B-P display order, the I-picture may be enhanced using a maximum of six integrable decoded frames (B-B-I-B-B-P), if only pictures possessing encoded half-pel motion vectors estimated with respect to the I-picture are considered. P- and B-pictures can also be enhanced using neighboring frames, but different pictures may be integrated. A maximum of seven decoded frames (I-B-B-P-B-B-P) can be integrated to enhance the first P-picture following an I-picture, while a maximum of three decoded frames (I-B-X-P or I-X-B-P) are integrable in the super-resolution enhancement of a B-picture. To calculate a Bayesian high-resolution video still (HRVS) estimate with an upsampling factor of $\uparrow r$ pixels, $1/(\uparrow r)$-th pel resolution motion vectors are required for all frames with respect to the picture undergoing enhancement. Adequate upsampled displacements can be estimated efficiently by utilizing the half-pel MPEG-encoded motion vectors as initial conditions to a reduced-search block matching algorithm. Improvements in visual quality can be quite impressive, provided that global frame transformations such as those produced by a camera pan are present within the sequence.

Embedding the Bayesian HRVS algorithm within an MPEG-1 decoder allows for the super-resolution enhancement of any frame within a compressed image sequence, although many empirical limitations have been discovered which affect the quality of the video stills. As a broad generalization, any intra-coded macroblocks that appear in a frame are capable of improving the visual appearance of the high-resolution video still far more than nonintra-coded macroblocks. This is intuitively obvious, since macroblocks that are only motion-compensated do not contribute additional information to the sequence. Experimentally, it has been found that integrating more than approximately four pictures from an arbitrary MPEG-1 sequence does not improve the quality of a super-resolution enhanced video still. A law of diminishing returns takes effect; *i.e.*, as additional pictures are integrated, more and more motion estimation errors leak into the enhanced frame, further degrading the image. Mosquito noise seems to be quite prevalent in the super-resolution enhancement of compressed video, apparently due to the integration of macroblocks compensated using inaccurate motion vectors estimated in the MPEG-1 encoder, as well as the integration of redundant information. For example, enhancing an I-picture through integration with its following P-picture usually results in a low-quality video still, since the P-picture consists primarily of forward-compensated macroblocks from the I-picture, and thus identical pixels between the two frames must be combined. Counterintuitively, the integration of I- and B-pictures provides higher-quality video stills than I-P integrations, most likely since the coded compensation differences in B-pictures are more significant than those present in P-pictures. By understanding the errors that can occur in the super-resolution enhancement of compressed video, it is possible to tune the MPEG-1 encoder to generate a video bitstream specifically tailored for high-quality super-resolution enhancement within the decoder.

Since the MPEG encoder uses block matching to compute motion vectors, the half-pel displacements estimated between the I-, P-, and B-pictures for a particular sequence can be obtained from an MPEG decoder directly. These MPEG half-pel motion vectors serve as an initial condition to a reduced-search block matching algorithm that calculates the $1/(\uparrow r)$-th pel motion vectors required for super-resolution enhancement. To estimate the displacements, the reference decoded I-picture and a second integrable frame

are first upsampled by a factor of $\uparrow r$ using cubic B-spline interpolation. Reduced-search block matching is then applied to these upsampled pictures, in which a relatively small search area is centered on an MPEG vector upsampled by a factor of $\uparrow r/2$. This dramatically reduces the amount of computation time required to calculate the motion vectors when compared to estimating the subpixel-resolution displacements using full-search block matching, with little apparent degradation in the super-resolution enhanced frame.

Simulations were conducted, in which six frames (B-B-I-B-B-P) were extracted from an MPEG-1 sequence coded at a compression ratio of approximately 10:1. These frames were first decoded and then integrated to compute the video still image. In general, it was found that I-picture enhancement improves with the integration of each additional B-picture, but deteriorates with each additional P-picture.

Further research was also conducted on the super-resolution enhancement of MPEG-2, the coding standard used in high-definition television (HDTV), digital video disk (DVD), and virtually all other commercial digital video products. A great need exists to improve the results of MPEG-2 enhancement, and the most likely area to make inroads on this task involves tuning the MPEG encoder for optimal super-resolution decoding. Compressed video contains little data redundancy, while the success of any super-resolution video enhancement algorithm is predicated on subpixel-resolution overlap (redundancy) of moving objects from frame-to-frame. By understanding the source of errors that can occur in the super-resolution enhancement of compressed video, it may be possible to tune the MPEG encoder to generate a video bitstream specifically tailored for high-quality super-resolution enhancement within the decoder. In essence, the MPEG encoder should be optimized to (1) increase the bitrate, since a low compression ratio inherently results in a coded sequence with more information than a high compression ratio; (2) turn on progressive scanning, in contrast to interlaced scanning which contains less data; (3) estimate motion vectors as accurately as possible; (4) place additional intra-coded macroblocks in regions of high motion, since intra-coded macroblocks contain the most information content, and the super-resolution enhancement of high activity regions is potentially fruitful; and (5) place additional intra-coded macroblocks along spatial edges within each picture, since super-resolution enhancement along discontinuities serves to dealias the video still.

The following conference publications/presentations based on this research were supported in part by this ARO grant:

Kyle J. Erickson and Richard R. Schultz, "MPEG-1 Super-Resolution Decoding for the Analysis of Video Still Images." In *Proceedings of the 2000 IEEE Southwest Symposium on Image Analysis and Interpretation*, pages 13-17, Austin, TX, 2-4 Apr 2000. Presented at the conference by Richard R. Schultz.

Debin Chen and Richard R. Schultz, "Extraction of High-Resolution Frames from MPEG Image Sequences." In *Proceedings of the 1998 IEEE International Conference on Image Processing* (on CD-ROM), Chicago, IL, 4-7 Oct 1998. Presented at the conference by Richard R. Schultz.

A **patent application** based on the enhancement of MPEG-1 and MPEG-2 compressed video was filed on 12 May 2000. This invention is based on research conducted by Kyle J. Erickson for his master's thesis, entitled "Super-Resolution Enhancement of MPEG Compressed Video," defended on 10 January 2000. Important information regarding the patent filing is provided as follows:

Patent Title:	"Super-Resolution Enhancement of Compressed Video Data"
Inventors:	Richard R. Schultz and Kyle J. Erickson
Assignee:	University of North Dakota
Filing Date:	12 May 2000
Serial Number:	60/133,765
Law Firm:	Shook, Hardy & Bacon L.L.P. (Kansas City, MO)
Attorney:	Mr. Michael J. Gross

5.4. Multiframe integration via the projective transformation with automated block matching feature point pair selection

A subpixel-resolution image registration algorithm based on the nonlinear projective transformation model is proposed to account for camera translation, rotation, zoom, pan, and tilt. Typically, parameter estimation techniques for transformation models require the user to manually select feature points between the images undergoing registration. In this research, block matching is used to automatically select correlated feature point pairs between two images, and these features are used to calculate an iterative least squares solution for the projective transformation parameters. Since block matching is capable of estimating accurate translation motion vectors only in discontinuous edge regions, inaccurate feature point pairs are statistically eliminated prior to computing the least squares parameter estimate. Convergence of the projective transformation model estimation algorithm is generally achieved in several iterations. After subpixel-resolution image registration, a high-resolution video still may be computed by integrating the registered pixels from a short sequence of low-resolution image sequence frames.

Empirically, it was determined that integrating more than approximately five raw (uncompressed) video frames does not significantly improve the spatial resolution of a particular frame, seemingly due to a law of diminishing returns. The quality of the enhanced imagery generated by this "quick-and-dirty" multiframe integration technique is certainly not as high as that obtained by Bayesian super-resolution video enhancement; however, this algorithm does not require nearly as many computational resources as Bayesian super-resolution enhancement, and an estimate can be calculated in several minutes rather than several hours. Moreover, this technique is effective in automatically registering channels acquired by dissimilar sensors, assisting in the fusion of data acquired by multiple sensors.

The following conference publications/presentations based on this research were supported in part by this ARO grant:

Richard R. Schultz and Mark G. Alford, "Automated Image Registration Using the Projective Transformation Model and Block Matching Feature Point Pair Selection." In *Proceedings of SPIE – Sensor Fusion: Architectures, Algorithms, and Applications III (AeroSense '99)*, volume 3719, pages 140-151, Orlando, FL, 7-9 Apr 1999. Presented at the conference by Richard R. Schultz.

Richard R. Schultz and Mark G. Alford, "Multiframe Integration via the Projective Transformation with Automated Block Matching Feature Point Selection." In *Proceedings of the 1999 IEEE International Conference on Acoustics, Speech, and Signal Processing* (on CD-ROM), Phoenix, AZ, 15-19 Mar 1999. Presented at the conference by Richard R. Schultz.

5.5. Development of a Windows-based software tool for the super-resolution enhancement of surveillance image sequences

With the intent of taking super-resolution enhancement algorithms from the research laboratory to the desktops of law enforcement agents, software designed for execution on a UNIX workstation has been ported to a personal computer running the Microsoft Windows NT operating system. To substantially reduce the number of computations required by the Bayesian high-resolution video stills (HRVS) algorithm, this technique can be applied to only critical regions within an image sequence. The user-friendly software package may be used by security, law enforcement, and military personnel to perform image sequence enhancement using their standard office computers without having to invest in high-end engineering workstations. Timing studies demonstrate that the *Mirage* video enhancement toolkit may outperform its UNIX ancestor on comparably-priced machines.

Because of the need for user-friendly super-resolution image sequence enhancement tools by forensic analysis laboratories, several research and development efforts conducted under the auspices of this ARO grant are being considered for technology transfer. Dr. Richard R. Schultz founded Multimedia Forensics in 2001, a North Dakota sole proprietorship specializing in software development for the digital video surveillance community. The intent is to further develop super-resolution enhancement technologies for law enforcement and national security agencies within the public and private sectors, with development efforts

surrounding the creation of video forensic plug-ins for the Adobe® Premiere® nonlinear digital video editing software package. The Principal Investigator is currently searching for a corporate partner to assist in the commercialization of relevant super-resolution enhancement technologies.

The following conference publication/presentation based on this research was supported in part by this ARO grant:

Kyle J. Erickson and Richard R. Schultz, "A Windows-Based Software Tool for the Super-Resolution Enhancement of Surveillance Image Sequences." In *Proceedings of the 1998 Midwest Symposium on Circuits and Systems*, pages 379-382, Notre Dame, IN, 9-12 August 1998. Presented at the conference by Kyle J. Erickson.

5.6. Super-resolution enhancement of night vision image sequences

Extensive prior research has been conducted on the Bayesian super-resolution enhancement of visible light image sequences. For night vision applications, super-resolution enhancement must be applied to image sequences with frames acquired in the thermal infrared region of the electromagnetic spectrum. Most of these applications are DoD-related, and they include the enhancement of infrared reconnaissance and surveillance imagery, as well as the enhancement of infrared imagery for automated target tracking and real-time multisensor fusion. Several computational simulations have been performed, which visually depict how well the proposed technique enhances short night vision image sequences consisting of two-to-five frames. This technique is capable of increasing resolution by factors up to 16x, although video stills appear somewhat blocky at higher magnification factors.

The following conference publication/presentation based on this research was supported in part by this ARO grant:

Darryl Sale and Richard R. Schultz, "Super-Resolution Enhancement of Night Vision Image Sequences." In *Proceedings of the IEEE Systems, Man, and Cybernetics Society 2000 Meeting* (on CD-ROM), Nashville, TN, 8-11 Oct 2000. Presented at the conference by Richard R. Schultz.

5.7. Spacecraft systems engineering – the initiation of a multidisciplinary design project at the University of North Dakota

During this past year, several departments at the University of North Dakota have been focusing on the design of inexpensive spacecraft for atmospheric studies and remote sensing. This multidisciplinary design project emphasizes the systems engineering approach, in which extensive design documentation is created prior to the build of subsystems and a multilevel system integration and test. Fourteen undergraduate and three graduate students designed and tested the second build of a spacecraft, known as Scorpio II, launched using a latex weather balloon in May 2001. This project was conducted to teach the students about systems engineering design principles, as well as to collect and transmit real-time sensor data from the atmosphere and digital images of the Earth's surface. The telecommunications subsystem is responsible for collecting sensor readings, acquiring images from a digital camera, and packetizing this data so that it can be transmitted to a ground station via a radio-frequency (RF) link. The RF link is implemented using a commercial, off-the-shelf (COTS) transceiver. Furthermore, the telecommunications subsystem is able to receive uplink telecommands for controlling image acquisition, vary the sampling frequency of individual sensors, and release the payload from the balloon. The spacecraft – attached to a parachute – can be tracked with global positioning system (GPS) data so that it may be safely recovered after its descent. The large-scale scope of this project, coupled with the group size, has led to many new experiences for the students, including an appreciation for true teamwork and the positive and negative aspects of group dynamics. The efficacy of applying this systems engineering approach to a variety of large-scale student projects, such as spacecraft or solar-powered vehicle design, is also discussed.

The following conference publications/presentations based on this research were supported in part by this ARO grant:

Chang-Hee Won, Darryl Sale, Richard R. Schultz, Arnold F. Johnson, and William H. Semke, "Spacecraft Systems Engineering – The Initiation of a Multidisciplinary Design Project at the University of North Dakota." In *Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition* (on CD-ROM), Electrical and Computer Engineering Division, Albuquerque, NM, 24-27 Jun 2001. Presented at the conference by Richard R. Schultz.

Christopher J. Schmidt, Joseph R. Rydel, Nicholas E. Hulst, Jonathan A. Lovseth, Darryl Sale, Chang-Hee Won, Richard R. Schultz, Arnold F. Johnson, and William H. Semke, "Design of a Balloon-Launched Spacecraft." Abstract presented by Christopher J. Schmidt, Joseph R. Rydel, and Jonathan A. Lovseth at the Northern State University Undergraduate Research Conference, Aberdeen, SD, 20-21 Apr 2001.

Christopher J. Schmidt, Jonathan A. Lovseth, Melissa A. Barnum, Jayson F. Clairmont, Patricia E. Langwost, Nicholas E. Hulst, Kelani J. Parisien, Joseph R. Rydel, Darryl Sale, Richard R. Schultz, Chang-Hee Won, Arnold F. Johnson, and William H. Semke, "Systems Engineering Pedagogy Through Balloon-Launched Spacecraft." In *Proceedings of the 2001 National Conference on Undergraduate Research*, Lexington, KY, 15-17 Mar 2001. Presented at the conference by Christopher J. Schmidt and Jonathan A. Lovseth.

6. Listing of All Publications and Technical Reports Supported Under this Grant or Contract

Provide the list with the following breakout, and in standard format showing authors, title, journal, issue, and date:

(a) Papers published in peer-reviewed journals

(b) Papers published in non-peer-reviewed journals or in conference proceedings

(c) Papers presented at meetings, but not published in conference proceedings

(d) Manuscripts submitted, but not published

(e) Technical reports submitted to ARO

In the following lists of publications, the names of all ARO-supported personnel are underlined. All lists are in reverse chronological order, according to the date of publication/presentation.

6(a) Papers published in peer-reviewed journals

1. Richard R. Schultz, Li Meng, and Robert L. Stevenson, "Subpixel Motion Estimation for Super-Resolution Image Sequence Enhancement," *Journal of Visual Communication and Image Representation*, volume 9, number 1, pages 38-50, Mar 1998.

6(b) Papers published in non-peer-reviewed journals or in conference proceedings

1. Chang-Hee Won, Darryl Sale, Richard R. Schultz, Arnold F. Johnson, and William H. Semke, "Spacecraft Systems Engineering – The Initiation of a Multidisciplinary Design Project at the University of North Dakota." In *Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition* (on CD-ROM), Electrical and Computer Engineering Division, Albuquerque, NM, 24-27 Jun 2001. Presented at the conference by Richard R. Schultz.

2. Richard R. Schultz, "Nonlinear Filtering of Subpixel Motion Vectors for Improved Super-Resolution Video Frame Enhancement." Invited paper in *Proceedings of the 2001 IEEE-EURASIP Workshop on Nonlinear Signal and Image Processing* (on CD-ROM). Presented in the Special Session on Nonlinear Methods for Signal Resolution Enhancement (Chairs: R. L. Stevenson and R. Hardie), Baltimore, MD, 3-6 Jun 2001. Presented at the conference by Richard R. Schultz.

3. Christopher J. Schmidt, Jonathan A. Lovseth, Melissa A. Barnum, Jayson F. Clairmont, Patricia E. Langwost, Nicholas E. Hulst, Kelani J. Parisien, Joseph R. Rydel, Darryl Sale, Richard R. Schultz, Chang-Hee Won, Arnold F. Johnson, and William H. Semke, "Systems Engineering Pedagogy Through Balloon-Launched Spacecraft." In *Proceedings of the 2001 National Conference on Undergraduate Research*, Lexington, KY, 15-17 Mar 2001. Presented at the conference by Christopher J. Schmidt and Jonathan A. Lovseth.

4. Darryl Sale and Richard R. Schultz, "Super-Resolution Enhancement of Night Vision Image Sequences." In *Proceedings of the IEEE Systems, Man, and Cybernetics Society 2000 Meeting* (on CD-ROM), Nashville, TN, 8-11 Oct 2000. Presented at the meeting by Richard R. Schultz.

5. Darryl Sale, Richard R. Schultz, Arnold F. Johnson, Trevor Timpane, and William H. Semke, "The Initiation of a Satellite Systems Engineering Program at the University of North Dakota." In *Proceedings of the 62nd Annual American Society for Engineering Education North Midwest Section Meeting* (on CD-ROM), Minneapolis, MN, 28-30 Sep 2000. Presented at the meeting by Richard R. Schultz.

6. Kyle J. Erickson and Richard R. Schultz, "MPEG-1 Super-Resolution Decoding for the Analysis of Video Still Images." In *Proceedings of the 2000 IEEE Southwest Symposium on Image Analysis and Interpretation*, pages 13-17, Austin, TX, 2-4 Apr 2000. Presented at the symposium by Richard R. Schultz.

7. Richard R. Schultz, "Experiences in the Integration of Digital Signal and Image Processing Research into the Undergraduate Electrical Engineering Curriculum." In *Proceedings of the 1999 American Society for Engineering Education Annual Conference & Exposition* (on CD-ROM), Charlotte, NC, 20-23 Jun 1999. Presented at the conference by Richard R. Schultz.

8. Melissa L. Kurtz, Allison D. Sawrey, Brian D. Pedersen, Mark J. Bailey, Scott B. Wing, Steve Lindaas, Richard R. Schultz, George Bibel, Arnold F. Johnson, and Charles A. Wood, "Design of the Telerobotic Adventures Web-Controlled Rover for the Dakota Science Center's Online Learning Environment." In *Proceedings of the 1999 National Conference on Undergraduate Research*, Rochester, NY, 8-10 Apr 1999. Presented at the conference by Melissa L. Kurtz.

9. Richard R. Schultz and Mark G. Alford, "Automated Image Registration Using the Projective Transformation Model and Block Matching Feature Point Pair Selection." In *Proceedings of SPIE – Sensor Fusion: Architectures, Algorithms, and Applications III (AeroSense '99)*, volume 3719, pages 140-151, Orlando, FL, 7-9 Apr 1999. Presented at the conference by Richard R. Schultz.

10. Richard R. Schultz and Mark G. Alford, "Multiframe Integration via the Projective Transformation with Automated Block Matching Feature Point Selection." In *Proceedings of the 1999 IEEE International Conference on Acoustics, Speech, and Signal Processing* (on CD-ROM), Phoenix, AZ, 15-19 Mar 1999. Presented at the conference by Richard R. Schultz.

11. Debin Chen and Richard R. Schultz, "Extraction of High-Resolution Frames from MPEG Image Sequences." In *Proceedings of the 1998 IEEE International Conference on Image Processing* (on CD-ROM), Chicago, IL, 4-7 Oct 1998. Presented at the conference by Richard R. Schultz.

12. Kyle J. Erickson and Richard R. Schultz, "A Windows-Based Software Tool for the Super-Resolution Enhancement of Surveillance Image Sequences." In *Proceedings of the 1998 Midwest Symposium on Circuits and Systems*, pages 379-382, Notre Dame, IN, 9-12 Aug 1998. Presented at the symposium by Kyle J. Erickson.

13. Kevin G. Rada, Richard R. Schultz, and Jody A. Rada, "*In Vivo* Depth Estimation of Features in the Chick Eye by Digital Signal Processing of Ultrasonic Pulse Echoes." In *Proceedings of the 1998 Midwest Symposium on Circuits and Systems*, pages 326-329, Notre Dame, IN, 9-12 Aug 1998. Presented at the symposium by Kevin G. Rada.

14. Richard R. Schultz, "A Practical Introduction to Digital Signal Processing through Microsoft Visual C++ and LabVIEW Programming." In *Proceedings of the 1998 American Society for Engineering Education Annual Conference* (on CD-ROM), Seattle, WA, 28 Jun 1998 through 1 Jul 1998. Presented at the conference by Richard R. Schultz.

15. Michael J. Carman, Aaron Douglas, Dawn C. Willett, and Richard R. Schultz, "Multispectral Segmentation of the Visible Human Project Data Set via Vector Quantization." In *Proceedings of the 1998 National Conference on Undergraduate Research*, Salisbury, MD, 23-25 Apr 1998. Not presented at the conference because of time constraints on personnel.

16. Richard R. Schultz and Robert L. Stevenson, "Estimation of Subpixel-Resolution Motion Fields from Segmented Image Sequences." In *Proceedings of SPIE – Sensor Fusion: Architectures, Algorithms, and Applications II (AeroSense '98)*, volume 3376, pages 90-101, Orlando, FL, 13-17 Apr 1998. Presented at the conference by Richard R. Schultz.

17. Richard R. Schultz and Robert L. Stevenson, "Bayesian Estimation of Subpixel-Resolution Motion Fields and High-Resolution Video Stills." In *Proceedings of the 1997 IEEE International Conference on Image Processing* (on CD-ROM), Santa Barbara, CA, 26-29 Oct 1997. Presented at the conference by Richard R. Schultz.

18. Richard R. Schultz, "Teaching Signals and Systems through Visualization with Image Processing." In *Proceedings of the 1997 American Society for Engineering Education Annual Conference* (on CD-ROM), Milwaukee, WI, 15-18 Jun 1997. Presented at the conference by Richard R. Schultz.

19. Melissa L. Kurtz and Richard R. Schultz, "Nonlinear Filtering and Enhancement of Digital Ultrasound Imagery." In *Proceedings of the 1997 National Conference on Undergraduate Research*, Austin, TX, 24-26 Apr 1997. Presented at the conference by Melissa L. Kurtz.

20. James A. Johnson and Richard R. Schultz, "SubzeroCam: Design of a World Wide Web-Based Digital Camera for Sunrayce '97." In *Proceedings of the 1997 National Conference on Undergraduate Research*, Austin, TX, 24-26 Apr 1997. Presented at the conference by Melissa L. Kurtz (proxy).

21. Richard R. Schultz, "A Hybrid Block Matching and Optical Flow Equation-Based Motion Estimation Algorithm for Digital Video Sequences." In *Proceedings of the ISCA 12th International Conference on Computers and Their Applications*, pages 74-77, Tempe, AZ, 13-15 Mar 1997. Presented at the conference by Richard R. Schultz.

22. Richard R. Schultz, Li Meng, and Robert L. Stevenson, "Subpixel Motion Estimation for Multiframe Resolution Enhancement." In *Proceedings of Visual Communications and Image Processing '97*, volume 3024, pages 1317-1328, San Jose, CA, Feb 1997. Presented at the conference by Richard R. Schultz.

6(c) Papers presented at meetings, but not published in conference proceedings

1. Christopher J. Schmidt, Joseph R. Rydel, Nicholas E. Hulst, Jonathan A. Lovseth, Darryl Sale, Chang-Hee Won, Richard R. Schultz, Arnold F. Johnson, and William H. Semke, "Design of a Balloon-Launched Spacecraft." Abstract presented by Christopher J. Schmidt, Joseph R. Rydel, and Jonathan A. Lovseth at the Northern State University Undergraduate Research Conference, Aberdeen, SD, 20-21 Apr 2001.
2. Kevin G. Rada, Jody A. Rada, and Richard R. Schultz, "An Automated Tissue Boundary Detection Algorithm for Ultrasonic Intraocular Studies Based on Digital Matched Filtering." Abstract presented by Kevin G. Rada at the 1999 Association for Research in Vision and Ophthalmology (ARVO) Annual Meeting, Fort Lauderdale, FL, 9-14 May 1999.

6(d) Manuscripts submitted, but not published

None.

6(e) Technical reports submitted to ARO

None.

7. List of All Participating Scientific Personnel

Mr. Bradley R. Bender, Graduate Research Assistant

B.S.E.E.:	University of North Dakota, May 1998
ARO Project:	"Digital Microscopy Image Analysis"
ARO Support:	Summer 1998

Mr. Bender was planning on attending graduate school at the University of North Dakota to work on this ARO project, but he decided to become a systems administrator within industry during the summer of 1998.

Mr. Kyle J. Erickson, Graduate Research Assistant

M.S.E.E.:	University of North Dakota, May 2000
B.S.C.S.:	University of North Dakota, August 1998 (Computer Science)
Master's Thesis:	*Super-Resolution Enhancement of MPEG Compressed Video*
ARO Projects:	"Super-Resolution Enhancement of Compressed Digital Video" and "Development of a Windows-Based Software Tool for the Super-Resolution Enhancement of Surveillance Image Sequences"
ARO Support:	Fall 1998, Spring 1999, and Summer 1999

Mr. Brian G. Giesinger, Undergraduate Research Assistant

M.S.E.E. (Expected):	University of North Dakota, May 2002
B.S.E.E.:	University of North Dakota, May 2000
Master's Thesis:	*Design of an Imaging System for AgCam – The International Space Station-Based Earth Observing Camera for Precision Agriculture*
ARO Projects:	"Design of a Weather-Balloon Launched Spacecraft" and "Digital Microscopy Image Analysis"
ARO Support:	Summer 1998 and Summer 1999

"AgCam" is a multidisciplinary research project between UND Engineering and the Upper Midwest Aerospace Consortium (UMAC), based at the University of North Dakota.

Mr. Nicholas E. Hulst, Undergraduate Research Assistant

B.S.E.E. (Expected): University of North Dakota, May 2002
ARO Project: "Design of a Weather-Balloon Launched Spacecraft"
ARO Support: Summer 2000

Mr. Hulst has been accepted to attend graduate school at the University of North Dakota starting in August 2002. He plans to serve as a graduate research assistant on the "AgCam" project.

Mr. Joseph R. Rydel, Undergraduate Research Assistant

B.S.E.E.: University of North Dakota, May 2001
ARO Projects: "Design of a Weather-Balloon Launched Spacecraft" and "Design of a World Wide Web Interface for the UND Space Studies Telescope"
ARO Support: Summer 1998 and Summer 2000

Mr. Darryl L. Sale, Research Engineer

ARO Projects: "Design of a Weather-Balloon Launched Spacecraft," "Super-Resolution Enhancement of Night Vision Image Sequences," and "Super-Resolution Enhancement of Compressed Digital Video"
ARO Support: Spring 2000, Summer 2000, Fall 2000, Spring 2001, and Summer 2001

Dr. Richard R. Schultz, Principal Investigator

Role in ARO Grant: Richard R. Schultz served as the P.I. of this ARO grant, supervising all project activities and documenting their results.
ARO Salary Support: Summer 1999, Summer 2000, and Summer 2001

Ms. Nicole A. Turner, Undergraduate Research Assistant

B.S.E.E.: University of North Dakota, May 2000
ARO Project: "Digital Microscopy Image Analysis"
ARO Support: Summer 1999

Ms. Turner is currently attending graduate school at North Dakota State University (Fargo, ND) in electrical engineering, performing research in biomedical and cardiovascular engineering.

8. Report of Inventions

Patent Application

Patent Title: "Super-Resolution Enhancement of Compressed Video Data"
Inventors: Richard R. Schultz and Kyle J. Erickson
Assignee: University of North Dakota
Filing Date: 12 May 2000
Serial Number: 60/133,765
Law Firm: Shook, Hardy & Bacon L.L.P. (Kansas City, MO)
Attorney: Mr. Michael J. Gross

9. Bibliography

None.

10. Appendixes

None.